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Definition of Initial Landing and Takeoff Reference Configurations for the High Lift Common Research Model (CRM-HL)

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The High Lift version of the Common Research Model (CRM-HL) is a geometry set developed to enable high lift configurations representative of those found on modern commercial airliners to be made available in the public domain. An effort is underway to create an ecosystem around this geometry set that will enable multiple users to collaborate on key common configurations that produce flow physics scenarios of shared interest. Such configurations will be referred to as reference configurations. Anticipated collaborative topics include CFD tool improvement and validation, technology development, and wind tunnel data acquisition methodology development. This paper will define two such reference configurations with the goal of establishing common geometry for these future efforts. It will include a discussion of the objectives for these configurations as well as the rationale behind their selection. It will also provide detailed configuration descriptions, broken down into the individual geometry elements.

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I. Introduction

The CRM-HL is heavily based on the CRM-HS (High Speed), the original version of the Common Research Model. The CRM-HS was created to fill a need for a commercial airplane geometry set with a modern cruise wing design that could be made available in the public domain for use in collaborative CFD validation studies, namely the highly successful Drag Prediction Workshop series. Most modern cruise wing geometry sets were based on commercial products which their manufacturers were reluctant to share. Those available in the public domain were based on dated designs. To fill the void, a modern aerodynamic wing design was incorporated into a generic wing planform that would be appropriate for a large twin-engine transport aircraft. The geometry was documented in an AIAA paper in 2008 [1] and was first studied in Drag Prediction Workshop #4 (DPW4) in 2009, and remained a focus of DPW5 in 2012 and DPW6 in 2016. The geometry has seen widespread use, including providing the basis for several wind tunnel models which have been the subject of numerous wind tunnel tests over the years.

For nearly as many years, the idea for creating an analogous geometry set for low speed configurations has been discussed in several forums where relevant, sharable geometry was desired. In 2013, NASA embarked on a technology development project that required a relevant platform for the application of Active Flow Control. In addition, a representative conventional high lift system was desired to provide a reference level of performance for the AFC configurations. This provided the impetus to develop the CRM-HL geometry set. Boeing developed a preliminary geometry set in late 2014 and in 2015, and it was reported on in early 2016 [2]. In addition, a range of leading and trailing edge positioning was defined for takeoff and landing for this geometry set as input for NASA to develop a 10% scale half model for the 14’x22’ wind tunnel at the Langley Research Center.

In late 2016, one set of the previously mentioned leading and trailing edge positioning was selected for use as the basis for two test cases for the first Geometry Meshing and Gridding Workshop (GMGW1) and the third High Lift Prediction Workshop (HLPW3), held concurrently at AIAA Aviation 2017. This configuration combined 30 degree inboard and outboard gapped slats with 37 degree inboard and outboard flaps. There were no leading or trailing edge

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brackets modeled, nor was there landing gear or horizontal tail. A nacelle and pylon were included, but there was not a nacelle chine. The two cases differed only in how the flaps were sealed to each other and to the body, with one utilizing partial chord sealing and the other no sealing. The same flap angle for both IB and OB angles was chosen to simplify the sealed case as well as to provide a range of challenge for the CFD codes with the inboard flap having less separation and the outboard flap expected to have greater levels of separation. It should be noted that the same basic geometry was also utilized in the fifth Higher Order CFD Workshop (HiOCFD5) in 2018 as well as the second Geometry Meshing and Gridding Workshop (GMGW2) in 2019.

The CRM-HL landing configuration specified for GMGW1 and HLPW3 was never intended to be an official reference configuration. It has always been the plan to test geometry in a range of positions in a wind tunnel before establishing reference configurations to a larger audience. It was deemed too risky to simply select a configuration based on CFD alone and then ask the larger community to expend a great deal of resources evaluating it, computationally or experimentally.

The first opportunity to wind tunnel test a CRM-HL configuration occurred in late 2018 during the first test of the NASA 10% half model in the 14'x22' subsonic tunnel at NASA Langley Research Center. Given that the primary test objectives were associated with AFC and that the test ended up short on time, only one set of leading and trailing edge positioning was tested. The intent was to use the same preliminary positioning as specified for GMGW1 and HLPW3. However, an issue with the model resulted in the spoiler trailing edges being misaligned at the junction of the inboard and outboard flap by roughly 0.1" model scale. The reason was traced to the outboard spoiler being trimmed too far forward. However, the outboard flap was positioned as if the spoiler trailing edge was in the right location. The result is that the flap has smaller overlap and larger gap than intended. This didn't make it an invalid configuration, just different than the intended geometry used in the workshop geometry. In addition, the testing of this configuration, plus a few more with a nacelle chine added in a few different positions, showed that a reasonable landing configuration could be achieved with this geometry set. In doing so, this limited amount of testing served to retire a significant amount of risk associated with the geometry.

A collaborative effort between NASA, Boeing, QinetiQ and the Aerospace Technology Institute led to an additional testing opportunity for the NASA 10% scale half model, this time in the QinetiQ 5 Metre Wind Tunnel. This test was conducted in late 2019 and provided an opportunity to collect force and moment, pressure and surface flow visualization data for a range of leading and trailing edge positions. While there were some unresolved half model testing issues described in the test summary [3] that obscured some of the true stall behavior, enough information was collected to enable the selection of one landing and one takeoff reference configuration.

II. Reference Configuration Objectives

The primary objectives of CRM-HL reference configurations are as follows:

- Present representative flow physics of interest for the intended uses.

  One of the main uses of this geometry will be in CFD development and validation efforts. The high lift community requires CFD tools that are capable of accurately predicting the flow phenomena that limit aerodynamic performance of high lift configurations [4]. This leads to the requirement to have these phenomena exhibited by reference configurations, preferably caused by representative geometric features. For example, one of the objectives for a maximum landing flap configuration is to maximize lift to minimize operational speeds. Configurations that push on these aerodynamic limits are notoriously difficult to analyze computationally as they often involve high levels of separation and multiple interacting three dimensional flow features. It is therefore desirable to have such a reference configuration exhibit these same features for the same reasons. It is important to have aggressive flap angles that push the limits of the flap boundary layers. It is important to have geometric features that replicate areas of wing boundary layer weakness that exist on real airplanes at high angles of attack such as behind the nacelle/pylon, near the body and in regions impacted by leading edge device support/bracket wakes. Also required is the ability to gather detailed flow field data in these different regions to compare with computations. In some cases, improvements in aerodynamic measurement technology may be required to do so. It might also be desirable to be able to remove some of the layers of geometric and flow field complexity to be able to study some of these issues in isolation. All of these factors are considered when picking reference configurations to study.

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- Provide reference performance metrics for a conventional high lift system.

  Another important use of the CRM-HL platform will be to use it as a basis for high lift technology development. Using a conventional high lift system is but one way to meet the performance requirements of a transport aircraft. Other approaches can be utilized such as the AFC wind tunnel example cited above. In that case, the conventional trailing edge flaps were removed and replaced by simplified flaps utilizing AFC. However, the performance metrics associated with this new system could be compared directly with those of a conventional system on the same wing of the same model in the same wind tunnel. Here, the conventional system provides a useful yardstick for measuring the capabilities of competing high lift architectures. Acting in this role, it is not required to have the absolute optimum conventional high lift system configuration, but having it be in the neighborhood of the optimum is desirable in order to have a useful comparison with other technologies.

- Be easy to replicate by a wide user base.

  Working with high lift geometry is difficult. There are many pieces that may need to be trimmed, merged, positioned, connected, intersected, etc. to arrive at a given configuration. Add to this sometimes differing ways that geometry is read, interpreted and processed by different CAD/geometry tools as well as variation in user proficiency and the story becomes even more complicated. While the CRM-HS has only a few configurations of interest possible from combinations of its limited number of surfaces, the CRM-HL has thousands possible from various combinations of surfaces, trims, positioning, sealing, brackets, gear, etc. The goal here is to provide the surfaces, boundary definitions and positioning information in the simplest, easiest to use way possible to reduce the chances of error in creating and reproducing any configuration, not just the reference ones.

III. Background

This section provides some general information about how the reference information that follows will be transmitted and some of the reasoning behind it. This is followed by a discussion about nomenclature related to reference configurations.

- All information for the CRM-HL will be provided in full scale inches.
- For surfaces that have "sharp" trailing edges, a common trailing edge thickness of 0.20" full scale has been adopted. While this is somewhat thicker than some trailing edges on current transports, it enables the geometry to be scaled down for a wind tunnel model to 5-6% and still have a model scale trailing edge thickness of 0.010-0.012". Any thinner would trigger manufacturing and robustness concerns. New surfaces with greater trailing edge thicknesses will likely need to be created to accommodate smaller scale models.
- All wing high lift devices will be defined in their stowed positions. This provides a known starting point for any future desired positioning.
- Wherever possible, surfaces will be provided that extend beyond their likely boundaries, as these boundaries can change, depending on how the geometry is used. This ensures that in cases where parts intersect, that a watertight intersection can be determined regardless of CAD system used. For example, the wing surface extends inward to well inboard of the body perimeter so that a definitive intersection between the two can be found. This process could be repeated should the wing-body fairing definition change.
- The definition of high lift device ends (surface boundary curves and end closure definition) will be defined in the simplest way possible, generally with one or two trim planes.
- "Local" coordinate systems will be utilized. In managing complex geometry, it is often useful to have elements defined in local coordinate systems, as it is usually easier and more intuitive to reference part locations to features that are aligned to coordinate axes that are aligned with the part. For example, the height of the outboard slat across the span could be measured as Z values in the body coordinate system. However, it would likely have more aerodynamic significance if measured as a distance from a Wing Reference Plane (Z = 0 in wing coordinate system), as this removes dihedral from the measurement. While

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all geometry associated with the CRM-HS and preliminary versions of the CRM-HL were provided to users in an airplane (or body) coordinate system, the final CRM-HL geometric elements will be provided in the coordinate system that is associated with each part, generally the one in which the surface or positioning information is defined. Information will be provided to enable geometry to be moved between different coordinates systems.

- A common way of communicating positioning will be used, whether it be moving high lift devices from stowed to deployed states or moving them between coordinate systems. It will be done by defining 3 orthogonal line segments representing the starting point of the transformation and another 3 defining the ending point. All CAD systems should be capable of creating coordinate axes from each set of lines and then creating a transformation between them that can be applied to geometric elements. The starting point axes can be located anywhere, but it is useful to have them positioned on or near some feature of the surface being moved so that the ending point axes show the actual motion of the feature, making errors easier to identify. While rather simplistic, this method has the advantage of only using line segments, simple elements that can easily be transferred between any CAD system.
- The default file format for transmittal of official CRM-HL information is STEP. There may be instances where additional file formats are used to accommodate special circumstances. While there should be no difference between them, if such a difference should arise, the STEP contents are to be considered the official source. Users of the official geometry may choose to save and transfer it in another format if it better meets the needs of their specific application (e.g. a CAD format for a wind tunnel model). However, it is suggested that geometry intended for general sharing be saved in STEP format.

It is useful to preface the reference configuration that follows with a discussion about nomenclature. A "configuration" is defined a singular geometric scenario assembled for a specific purpose or application, whether it be for input into a CFD analysis code or as modeled in a wind tunnel. These can range from very simple (e.g. a fuselage and cruise wing configuration) to very complex (e.g. a full landing configuration, inclusive of trimmed, deployed high lift devices, and all brackets, fairings and sealing between elements). It's important to note that while a complex configuration can be simplified by removing things like brackets, fairings and sealing, that the result is a different configuration, in spite of the fact that all of the primary surfaces and their positioning maybe identical. All of this makes the task of documenting configurations much more difficult, as all of the details need to be captured in doing so.

A configuration is generally described by a combination of some or all of the following items:

1. Surfaces
2. Surface boundaries (trims and closure information), can included cavity definitions
3. Positioning of the trimmed surfaces relative to one another
4. Sealing between the positioned, trimmed surfaces (e.g. gaps on a wind tunnel model sealed with tape)
5. Representations of high lift device brackets and associated fairings, exposed routing of instrumentation, etc. (generally application-specific items)

It should be noted that the items in the last category will be difficult to replicate across all applications attempting to use a common configuration. For example, differences in wind tunnel model scale, loads and levels of instrumentation might result in differences in bracket shape and size that cannot be avoided. These variations will have to be described in the configuration documentation for these applications. However, in circumstances where variation is likely, guidance will be provided regarding how to best accommodate the required changes while minimizing the aerodynamic impact.

The term of "reference" is applied to surfaces, positioning and configurations that are deemed to be of use to the community at large. As such, they will have official documented definitions that will be available to the public and be accessible via the CRM-HL page on the NASA Common Research Model website (https://commonresearchmodel.larc.nasa.gov/high-lift-crm/).

Reference surfaces refers to the basic surface definitions. These will be the building blocks for all configurations that are created. An initial set has been defined and will be discussed below. However, others could be added later. These could take the form of new high lift devices that differ in type, size and/or shape or perhaps a different nacelle and pylon installation.

Reference positioning refers to rigid body transformations that get applied to reference surfaces to produce positioned geometry of specific interest, usually in support of reference configurations. These will be created and transmitted as sets of line segments that can be used to define a transformation as described above. They will be logged with the surface they are to be applied to, information about how they were created, and additional information that can be used to validate proper usage (e.g. resulting gaps, etc.).

The single source of reference information will be the NASA CRM website, so it will not be duplicated here.

IV. Reference Surfaces

The initial reference surfaces are described below. Key characteristics are provided along with details about differences from the preliminary geometry that has been used to date. The coordinate system used for each surface is also noted.

A. Fuselage (Airplane Coordinate System)

The fuselage is defined in the Airplane Coordinate System, sometimes referred to as the Body Coordinate System. The definition has its roots in the CRM-HS body, which was made up of many different patches. Unfortunately, there were issues at some of the patch boundaries that made it difficult to close it into one watertight shape. Several attempts have been made to improve this geometry, including several modifications leading up to the GMGW1/HLPW3 workshops. Still further refinement was done for GMGW2, which led to the current geometry.

The current definition still consists of multiple faces, the topology of which can be seen in Figure 1. This geometry still maintains the detail of the original definition, specifically the discontinuities that exist between the wing-body fairing and fuselage "tube" and around the windshield. While some of the surfaces are rather dense (and perhaps could have been simplified with no perceivable aerodynamic difference), they've proven to be usable by multiple parties, so they are being left in their current state.

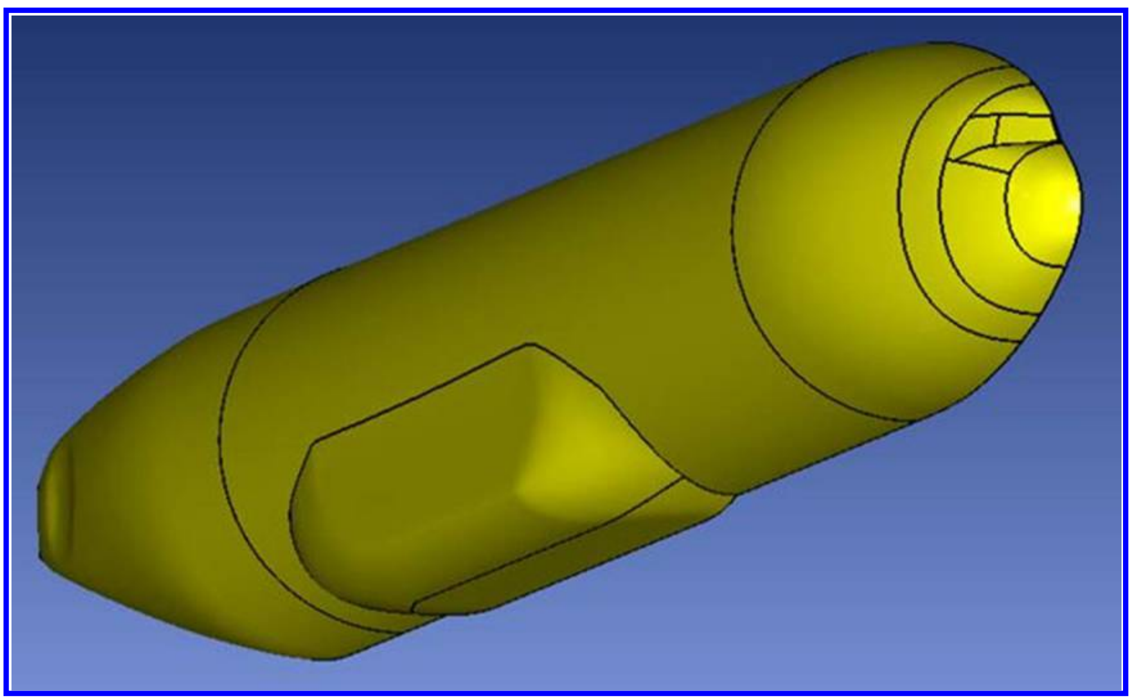

Figure 1 Topological view of GMGW2-based reference fuselage definition.

B. Wing (Wing Coordinate System)

The final wing specification for the CRM-HL is numerically identical to the preliminary one developed in 2015+, but is now provided in Wing Coordinate System. However, the main wing surface has been broken up into 6 pieces

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to allow the span-wise discontinuity introduced by the slope break in the trailing edge to be isolated to the boundaries between surfaces. First, the wing is split into inboard and outboard portions at the trailing edge break. Next, both of these sections are divided into three pieces: an upper surface trailing edge portion, a lower surface trailing edge portion, and the rest of the section. The trailing edge pieces isolate the sections of the wing that have discontinuities across their shared boundaries. The forward sections have slope and curvature continuity across their shared boundary. The resulting topology can be seen in Figure 2.

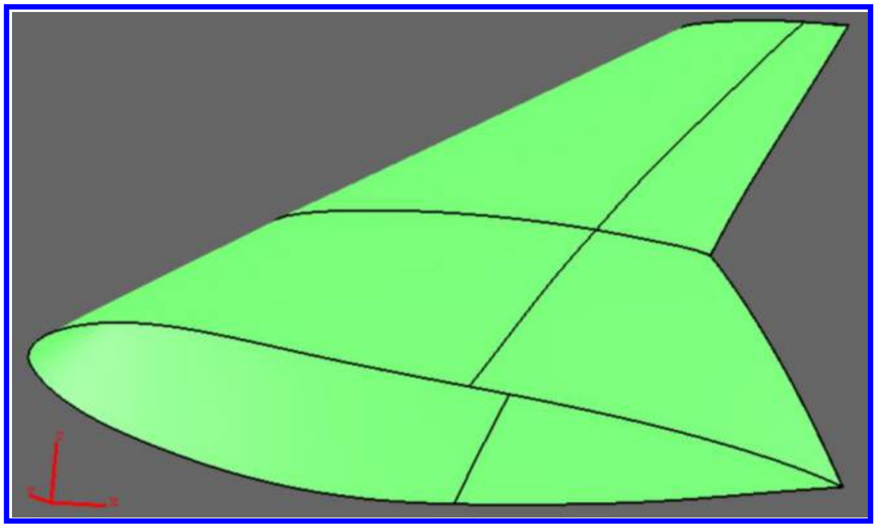

Figure 2 Topological view of reference wing surface.

This wing is heavily based on the CRM-HS cruise wing, utilizing the original defining airfoils. However, there are a few significant differences summarized below. Additional details can be found in the 2016 paper.

- Leading edge curvature modifications to make more amenable to low-speed operation
- Span-wise straightening for easier implementation of high lift devices
- Positioned in wing coordinate system

Figure 3 compares the front view in airplane coordinates of the CRM-HS wing with that of the CRM-HL wing. A line representing the wing reference plane (Z=0 in wing coordinate system) is included for reference. As can be seen, the CRM-HL wing is well centered on this line, and the 5 degrees of dihedral incorporated into the positioning of the wing coordinate system capture the effective dihedral in the CRM-HS wing. The introduction of a wing coordinate system will simplify the definition of high lift device positioning as well as enable simplification of wind tunnel model parts based on the wing geometry.

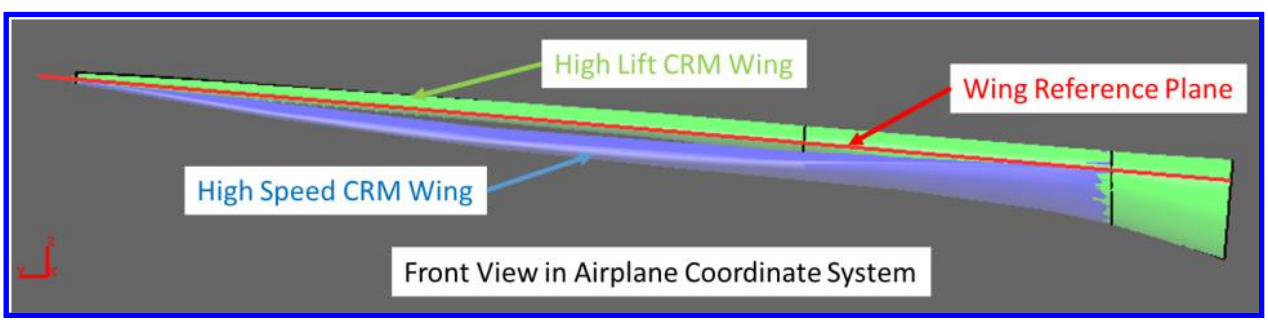

Figure 3 Front view comparison of high speed (blue) and high lift (green) wing surfaces. Wing Reference Plane is shown in red for reference.

The primary wing surface was defined without a strake, as it's based on the CRM-HS which also does not include one. However, a separate strake surface has been defined for this wing. There is also a simple rounded wing tip cap surface provided to close the outboard end of the wing.

C. Nacelle and Pylon (Nacelle Coordinate System)

The nacelle and pylon surfaces are both based on those from the high speed CRM. However, both have seen modifications leading to their definitions for the high lift version.

For the preliminary nacelle cowl, the surface was defined as a single surface that had been modified to open the trailing edge to the desired 0.20". CFD analysis during the initial design indicated that the nacelle lip would not separate until after the wing stalled and therefore did not impact C_{Lmax}. However, these events were predicted to occur fairly close together in angle of attack. In hindsight, modifications to the cowl lip should have been made then to push the cowl separation to a higher angle of attack in order to not have it complicate an already complex flow field in this portion of the wing near stall, particularly since this separation would not exist at this angle of attack on a real airplane with engines running. However, this was not done. Consequently, testing at QinetiQ revealed that the cowl separated almost coincident with stall. Therefore, for the reference nacelle, the cowl lip has received a small modification to enable it to reach higher angles of attack without separating. The resulting surface has also been broken into inner and outer portions, and those into inboard and outboard sections, resulting in a total of four surfaces.

The high speed CRM pylon was defined in a way that resulted in a far more complicated surface than was desired for the CRM-HL. It also was long enough that it overlapped the leading edge of the newly-defined trailing edge flaps, another complication that was deemed unnecessarily complex as well as not representative of most modern aircraft. Therefore, a simpler surface was developed to capture the shape of the high speed pylon over the forward portion, to shorten the aft portion by 12.0" (to close ahead of the flaps) and open the trailing edge to the desired 0.20". Unfortunately, this simplified had some slight "wrinkling" in the complex curvature areas. The choice for the reference pylon was whether to go back to a more complex definition to avoid the wrinkles or keep the simpler surface. Given that the simpler surface had presented no issues for CFD or wind tunnel model design thus far, and the wrinkling seemed to have no meaningful aerodynamic impact, it was chosen for the reference definition.

The positioning of the nacelle and pylon relative to the wing is unchanged from the earlier definition. It provides the same relative nacelle and pylon to wing relationship on the new, straightened wing as exists with the high speed CRM geometry set. The reference nacelle and pylon are now provided in a nacelle coordinate system that is aligned with the nacelle cowl. Coordinate axes transformations can be used to position it properly in other coordinate systems.

D. Leading Edge Slats and WUSS (Leading Edge Coordinate System)

The leading edge slat and Wing Under Slat Surface (WUSS) geometry is defined in the leading edge coordinate system. This coordinate system is defined as the wing coordinate system rotated about its Z-axis by sweep of the wing leading edge, thus unsweeping the wing leading edge. Therefore, constant Y cuts will be normal to the leading edge of the wing as well as normal to the wing reference plane, and provide a convenient orientation to create, position and analyze the leading edge devices.

It was desired to be able to create configurations without the nacelle and pylon, but with a continuous deployed leading edge and smooth transition between inboard and outboard slats. This required common geometry at the boundary between inboard and outboard slats and WUSS's. To enable this, an inboard/outboard break between slats was chosen near the nacelle centerline, on a normal-to-leading edge cut. The chord of the inboard slat, measured in plan view, normal to the leading edge, is a constant 26.0". The outboard slat starts at the same chord at the defined break, and tapers down to 20.0" at its outboard end. Both the inboard and outboard slats are created as single pieces and are positioned as such.

The inboard and outboard slat outer surfaces are essentially the wing loft near the leading edge, and they could have been cut directly from the wing. However, instead they have been recreated from constant Y cuts of the wing in the leading edge coordinate system. The main difference between these recreated surfaces and the wing loft itself is in how the surfaces area parameterized, as dimensionally, they are very close to the same.

Slat inner surfaces have been created that are representative of those of slats on modern aircraft with two exceptions. First, the upper and lower trailing edge thicknesses have both been set to 0.20". This is thicker that typical, but required to meet manufacturing constraints for envisioned wind tunnel models. Second, sharp corners have been filleted, likewise to facilitate their use in fabricating wind tunnel model parts.

The inboard and outboard WUSS definitions were designed to produce reasonable pressure distributions for both a nominal 30 degree landing position and a 22 degree takeoff position using a simplistic approach to positioning – a simple rotation about a defined axis for each surface. However, final surface positioning was always subject to change once wind tunnel data were gathered.

In a chord-wise sense, both WUSS's blend back into the cruise wing 1.5" aft of the stowed slat trailing edge on both the upper and lower surface, as measured in the X direction in leading edge coordinates. The provided surface

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definitions extend further aft than this, where they continue to approximate the wing surface. Both surfaces extend in a span-wise sense in both directions beyond their anticipated boundaries.

As mentioned previously, the slat trailing edge thicknesses are an unrealistically large 0.20”. However, the WUSS surfaces were defined assuming thinner slat trailing edges to provide a more realistic blend back into the cruise wing. This means that these slats, as currently defined, cannot be stowed without interference. This was deemed acceptable, as the cruise leading edge configuration is typically modeled for wind tunnel testing by utilizing a separate set of parts cut directly from the wing surface as opposed to using the slats with zero degree brackets.

E. Trailing Edge Flaps (Wing Coordinate System)

Inboard and outboard single-slotted flaps are defined in the wing coordinate system. The outboard flap is nominally 25% of the wing chord. The inboard flap has the same chord at its boundary with the outboard flap, and is nominally constant across the span. However, both flaps only have these nominal chords at their ends. In between, the chord distributions are bowed forward a small amount in order to help maintain more uniform gaps distributions when the flaps are deployed.

Inboard and outboard flap cove surfaces have also been defined that serve to locate the upper and lower wing trailing edge locations when the flaps are deployed. The lower cove edges are configured to approximately touch the lower nose of the stowed flap surfaces while the upper edges represent the spoiler trailing edges. The spoiler trailing edges are defined on the wing surface at 40% of nominal chord for each of the flaps. The upper and lower trailing edge thicknesses resulting from these cove surfaces measure 0.20”. Unlike the WUSS’s, the flaps have been designed to accommodate the trailing edge thicknesses of the surfaces in front of them, meaning that the flaps can nominally be nested in the stowed positions without interference. The aerodynamic impact of accommodating the spoiler trailing edge thickness in the flap design was deemed minimal. It should be noted that while the flap surfaces can be stowed, the simplest, most repeatable method to model a cruise trailing edge in the wind tunnel is to fabricate separate cruise parts from the wing loft.

The flaps could have been defined as surfaces only in the regions where they are not coincident with the wing, with the remainder being defined by the wing surface (most of the flap lower surface and the after region of the upper surface). However, they were instead defined as single surfaces that include the portions that represent the wing. In these coincident regions, the flap surface very closely approximates the wing.

F. Horizontal Tail (Horizontal Tail Coordinate System)

The horizontal tail surface is taken from the high speed CRM definition, with the only modification being to establish a trailing edge thickness of 0.20”. The surface definition includes an integrated strake at the leading edge intersection with the fuselage. The surface is provided in the Horizontal Tail Coordinate system, which is analogous to the wing coordinate system. The entire surface is intended to be able to rotate about a $Z = 0$ axis that is parallel to the Y-axis and passes through the 25% mean aerodynamic chord point. The sides of the fuselage have been tailored appropriately for this motion. On a related note, a vertical tail has not yet been defined, but is planned, and will have its own coordinate system.

G. Main Landing Gear (Airplane Coordinate System)

A four wheel truck wing-mounted main landing gear has been developed by NASA. While an aircraft of this size might actually require a 6-wheel truck or a main body gear, the 4 wheel configuration was deemed sufficient for the purposes of this geometry set. Much of the typical detail is modeled with high fidelity on this gear to make it suitable for acoustic evaluations. A simpler version which strips away many of the details, leaving only the primary structural elements, is planned. The simpler gear will likely be the primary version used for most studies. A wing lower surface cavity definition accompanies the gear definition. A nose gear has not yet been defined, but one is planned.

H. Aileron (Wing Coordinate System)

An aileron hinge line has been defined in the wing coordinate system. In plan view, it has a chord of 22% of local wing chord. Vertically, the hinge line is positioned with an approximately equal offset below the wing upper surface. A preliminary offset has been established, and it will be formalized when published on the website. The aileron surface geometry will then be a fallout of rotating about this hinge line through an expanded rotational range (likely+/-30 degrees).

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V. Positioning for Reference Configurations

Positioning for the leading and trailing edge high lift devices for both a landing and takeoff configuration have been defined based on the objectives above and the wind tunnel testing conducted to date.

Leading edge slat positioning for the pretest nominal takeoff and landing configurations was achieved through simple rotations about a defined axis. Positions for variation in angle around each position were generated by rotating the nominal deployed slat about its effective trailing edge. While this was fine for a limited preliminary geometry set, a more generic approach is desired for the reference geometry. Since all transformation information will be transmitted via axes as described earlier, the emphasis is no longer on how the positioning is created, but rather to be able to verify it once it is applied. Leading edge angles will no longer be about an arbitrary axis, but instead will be the effective angle about the Y axis in Leading Edge Coordinate system. The simplest way to describe (or verify) this angle for a given transformation would be to start with a Z=0 plane in this coordinate system, apply the transformation to this plane to create a new plane, then take a constant Y cut (in Leading Edge Coordinates) of both planes. The angle between the two lines is the leading edge angle, with leading edge down defined as a positive angle.

The other leading edge positioning variables are slat trailing edge height and gap. The height is measured from the slat trailing edge on the upper surface to the wing reference plane (Z=0 in wing or leading edge coordinates). Gap is measured as the shortest 3D distance between the slat trailing edge and the WUSS. Note that the leading edge transformations are to be applied to stowed slats in the leading edge coordinate system (the system in which they are now defined).

Heights and gaps will usually be expressed in non-dimensional form by dividing by a reference chord (Cref). For the leading edge, the reference chord is the local trapezoidal wing chord (i.e. the wing Yehudi is not included).

Trailing edge positioning for the pretest nominal configurations was already defined in a similar generic fashion. Angle would be as defined above for the leading edge, except that the constant Y cut of the two planes would be done in the wing coordinate system. This represents a stream-wise angle for the wing. However, rather than height and gap being used to set vertical and horizontal positioning, respectively, gap sets the vertical position and overlap sets the horizontal. Overlap is defined as the X distance in wing coordinates between the spoiler trailing edge and flap leading edge. Positive values denote that the flap leading edge is forward of the spoiler trailing edge. Similar to the leading edge, gap is a measure of the shortest 3D distance from the spoiler trailing edge to the flap surface.

As for the leading edge, trailing edge gaps and overlaps will also usually be expressed in non-dimensional form by dividing by a reference chord. For the outboard flap, the reference chord is the local wing chord. For the inboard flap, it is a constant value equal to the wing chord at the wing trailing edge break.

The leading and trailing edge positioning parameters are depicted in Figure 4.

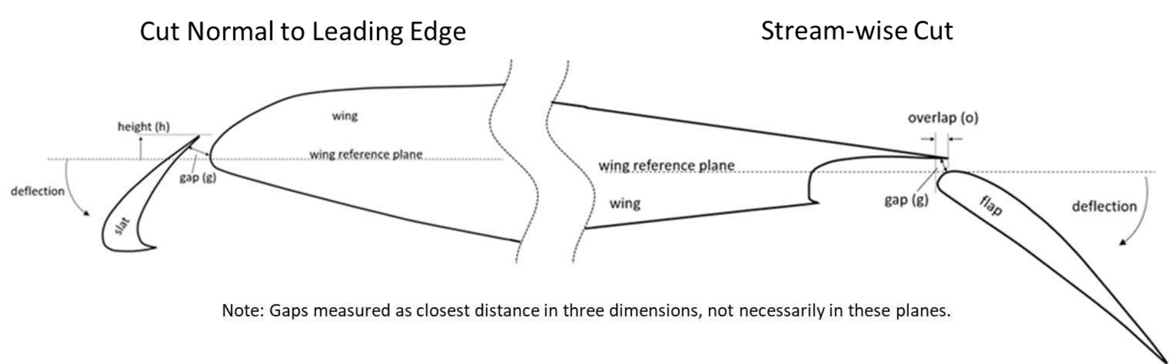

Figure 4 Leading and trailing edge device positioning parameters.

The high lift device surfaces have all been defined in a span-wise sense beyond where the actual surfaces exist. As such, they must be trimmed in ordered to avoid interference, either in the stowed or deployed positions. As a general rule, this trimming is done with the surfaces in their stowed (as defined) positions, as the trimmed stowed surfaces can then be deployed to multiple positions. However, the definition of these surface boundaries is often defined as those required to avoid interference for the range of deployed positions. This often results in the surfaces being trimmed back more than any one position would require, necessitating adding back some “sealing” between some surfaces to

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more accurately replicate the real airplane scenario. For this geometry set, these trims have been made in the simplest way possible by specifying one or more trim planes to use to bound a given end of a surface. It should also be noted that these trimming and sealing details are part of any configuration and therefore must be documented as such.

For the inboard and outboard slats, their inboard ends are defined by stream-wise cuts, or in other words, constant Y planes in wing coordinate system. Since these devices move generally normal to the wing leading edge, the trims on the slats move away from the trims on the wing side as the slats deploy, so there is no chance for interference when deployed. Their outboard ends are defined by constant Y cuts in leading edge coordinate system, so the slat and wing side boundaries stay close to each other during slat deployment, offering the potential for interference at some positions. Because of this, the slat and wing trims are offset slightly to prevent such interference.

For the flaps, plane definitions have been developed for each end of each flap that keep adjacent surfaces from interfering through the range of prescribed positioning. This results in some unrealistically large gaps between them at their interface which must be sealed to some degree to mimic a real aircraft scenario. These are generally defined as a connection that seals the flaps together from the flap noses aft to within some distance from the trailing edge of one of the flaps. This distance generally increases (sealing reduces) as flap angles increase.

To adhere to the philosophy of a single source for positioning information, that being the NASA CRM-HL website, only approximate positioning information will be provided here. The rationale for choosing these positions will be discussed with the wind tunnel results in a later section.

A. Landing Reference Configuration Positioning

In the reference landing configuration, the inboard and outboard slat angles are 30 degrees. While this is the same value as the pretest nominal, the positioning is slightly different due to the difference in how the angles are defined. The inboard and outboard gap distributions have been increased by 0.003*Cref relative to the pretest definition. The height distribution has also been raise across the span of the inboard and outboard slats by 0.005*Cref.

Relatively minor changes were made to the pretest trailing positioning as well. The inboard flap angle was increased to 40 degrees, the next higher test increment available above 37. The outboard flap remains at 37 degrees. Overlaps remain essentially unchanged, and gaps have been reduced somewhat from their pretest values. Stream-wise sectional cuts of the positioned geometry mid-span of the inboard and outboard flaps are shown in Figures 5 and 6, respectively.

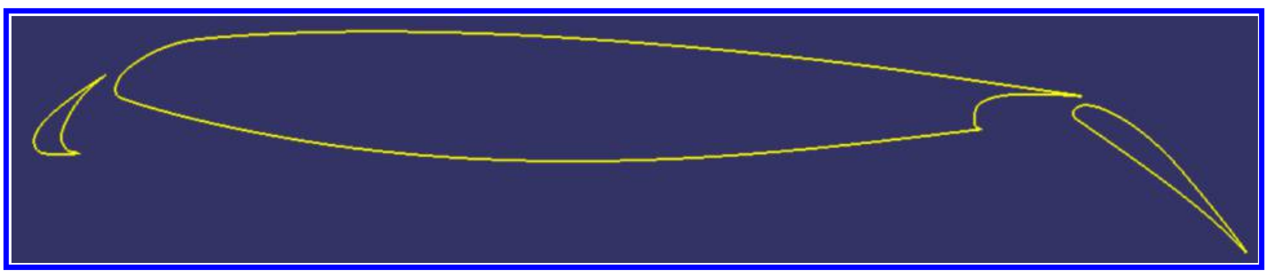

Figure 5 Inboard sectional cut (Y=300) of the reference landing configuration.

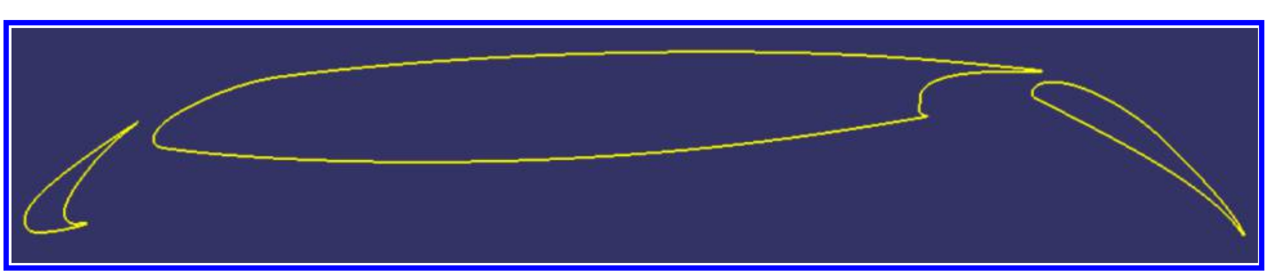

Figure 6 Outboard sectional cut (Y=780) of the reference landing configuration

B. Takeoff Reference Configuration Positioning

In the reference takeoff configuration, the inboard and outboard slat angles are 22 degrees. Again, while this is the same value as the pretest nominal, the positioning is slightly different due to the difference in how the angles are defined. The gap distribution has been changed from having a small gap to having no gap. During wind tunnel testing, the underside of the slats was taped to the WUSS's in order to ensure complete sealing. The height distribution remains as its pretest nominal.

While the original plan was to gather data for flap angles of both 10 degrees and 25 degrees, issues with the 10 degree flap brackets and a shortage of test time resulted in testing only the 25 degree flaps. While the gaps were varied during testing, the reference gaps and overlaps remain unchanged from pretest nominal.

VI. Brackets, Fairings and Wing Pressure Layout

At this point, all surfaces have been discussed and all high lift devices have been trimmed and positioned. This section will provide guidance on how to connect the high lift devices to the wing. Clearly, it is desired to make these connections look as much as possible like the connections on real airplanes. Efforts along these lines are explored below. One of the factors influencing where the leading and trailing edge supports are located is the desire to locate stream-wise pressure rows in regions not occupied or excessively influenced by brackets or device end effects. A summary of wing pressure row and bracket locations is provided at the end of this section.

A. Leading Edge

For an airplane of the size of the CRM-HL, one might expect to see a singular slat for the inboard span and six slats across the outboard span. The inboard slat is long enough that it would probably require three supports (usually tracks). These might be distributed at approximately 20, 50 and 80 percent span of the device. Here, they have been set to 25, 50 and 75 percent span to better accommodate wind tunnel model pressure taps as well as provide more design flexibility. The outboard slats could be supported with two tracks each, spaced at 25 and 75 percent span of each slat. While it's common to have a different individual slat spans across the outboard wing, they're assumed to be roughly constant span here. This logic established the number of support elements that would be incorporated (three inboard and twelve outboard) and their locations across the span.

When these supports are modeled on a wind tunnel model, they don't all have to be structural supports. For the inboard slat, the outer supports could be structural and the middle one non-structural and act as a conduit for instrumentation. (It could be attached at one end and left to float on the other.) The outboard slats do not all have to be modeled as individual slats, and can be modeled together as combined pieces. The six slats could be made as three sets of two slats, two sets of three slats, or a single piece for the entire span. In that case, it could use twelve structural brackets or some combination of structural and non-structural brackets that is appropriate for the model loads and instrumentation requirements. Regardless of slat segmentation, all instrumentation routing should be done through these support elements.

Regardless of whether the "support elements" are structural or not, it is desired that they all be architected in the same way. Ideally, this would mimic real airplane supports. These are usually circular arc tracks that extend through the front of the WUSS. However, there is a significant amount of variability that can be introduced with brackets configured in this way, particular in regards to providing slat adjustability, as this generally results in large cutouts in the WUSS to accommodate bracket movement. In order to simplify the configuration and help promote consistency across users, a different bracket approach is specified here. Instead of brackets extending through the nose of the WUSS, they will come out underneath it. On the slat side, the "foot" of the bracket should be recessed into the vertical back side of the slat. On the wing side, the bracket foot should be attached within a recessed pocket in the wing and covered with a wing-contoured cover plate. The connection between these feet should be a simple shape that departs the wing recess no further forward than where the high curvature area of the WUSS lower nose begins. It should then take the simplest path possible to the foot on the slat side that does not cut through the inner or outer slat surfaces. All leading edge brackets should also be centered on constant Y planes in leading edge coordinate system, i.e. they should be normal to the cruise wing leading edge.

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The cross-sectional shape of the bracket should be generally rectangular. However, portions of the cross-section can be removed for routing of instrumentation. For example, it could have a “U” cross-section. The critical dimension is the width (Y-dimension). Typical slat tracks can be on the order of 3-4” wide. Here, a width of 3.875” has been selected for the brackets. The height of the cross-section should be minimized, but if addition section is required for strength or instrumentation, height should be increased before width.

An example of this bracket architecture as implemented on the NASA 10% scale model is shown in Figure 7.

Figure 7 Leading edge bracket example with internally routed pressures.

B. Trailing Edge

A typical airplane flap will have two primary supports. An outboard flap typically has them positioned at in the vicinity of 25 and 75 percent span. Often inboard flaps will position the inboard support inside the wing-to-body fairing to eliminate the drag of an addition support fairing. This body bracket approach has been adopted for the CRM-HL. The other inboard support has been positioned at approximately 70 percent of the flap span. The supports on the outboard flap have been placed at approximately 25 and 78 percent flap span. These selections were made with consideration for desired pressure row locations. It should also be noted that all on-wing locations are different from those on the NASA 10% scale model.

Since the flap support mechanisms are generally covered by fairings, bracket requirements mostly boil down to staying within the fairings. However, keeping the flap-side bracket feet well aft of the flap leading edge desired, as is keeping the wing-side bracket feet ahead of the lower surface trailing edge of the flap cove. It is also desired to keep all flap instrumentation routed either through fairings or directly into body through the inboard flap.

The chosen flap support implementation starts with a full cruise wing fairing. The fairing is split into forward and aft portions. The forward portion is fixed to the wing. The aft portion rotates trailing edge down around a hinge line near the bottom of the fairing at the split. The amount of rotation increases with flap deflection to enable the fairing to clear the flap.

Flap support fairings were developed by NASA for their 10% scale model with guidance on width, depth and length. They are not aerodynamically designed for high speed, but more than adequate for low speed. The plan was to continue to use these fairings, but they are currently being modified to work with the revised flap support locations. Once complete, the fairings, split definitions, hinge line definitions and rotation schedule will be made available.

C. Wing Pressure Rows

Recommended pressure locations will be provided for the wing, nacelle, pylon and fuselage so that multiple users can compare their results. For the wing, a “kinked cut” approach to wing stream-wise pressure rows has been adopted. Pressures are arranged normal to the leading edge for the leading edge devices and for the wing until the 25% of trapezoidal wing chord span-line is reached, aft of which, pressures are located on constant Y plane in wing coordinates. Figure 8 shows the location of these pressure rows as well as representations of leading edge brackets and trailing edge fairings.

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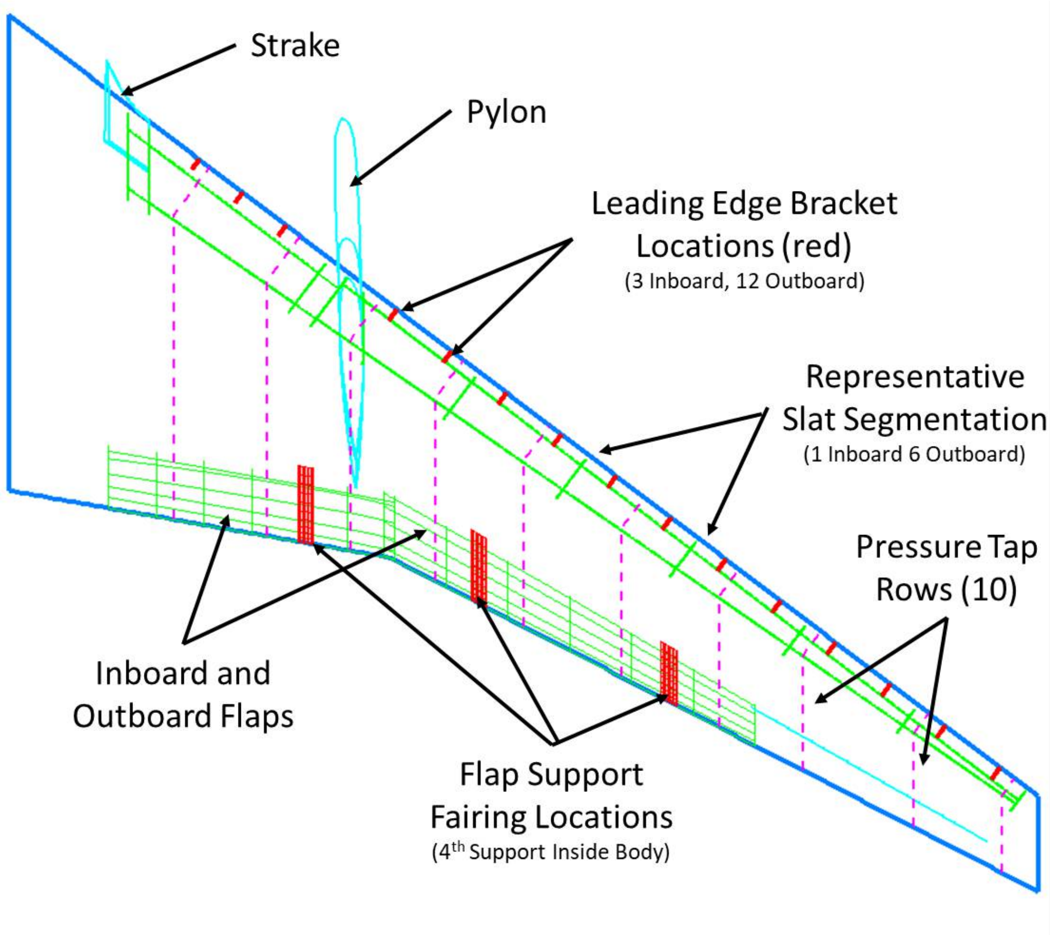

Figure 8 Leading edge bracket example with internally routed pressures.

VII. Reference Configuration Characteristics

A. Landing Reference Configuration

As mentioned previously and discussed in more detail in the QinetiQ test summary [3], some half model testing issues appeared to obscure the true high angle of attack behavior of the model. When floor boundary layer blowing was used, the results better matched results collected on the same model in the NASA Langley 14’x22’ wind tunnel, particularly in regards to how the wing stalled. Figure 9 shows two lift curves, one with blowing and one without, for a configuration close to the landing reference configuration. First, it can be seen that it is producing reasonably high lift levels, both at lower angles of attack and at stall, and stall is occurring at a representative angle of attack. Second, one can see the improvements due to floor blowing, particularly at higher angles of attack. Lastly, the effect of early separation on the nacelle lip can be seen in the form of a notch in the lift curve near stall. This feature has been removed by modifying the nacelle lip as mentioned previously.

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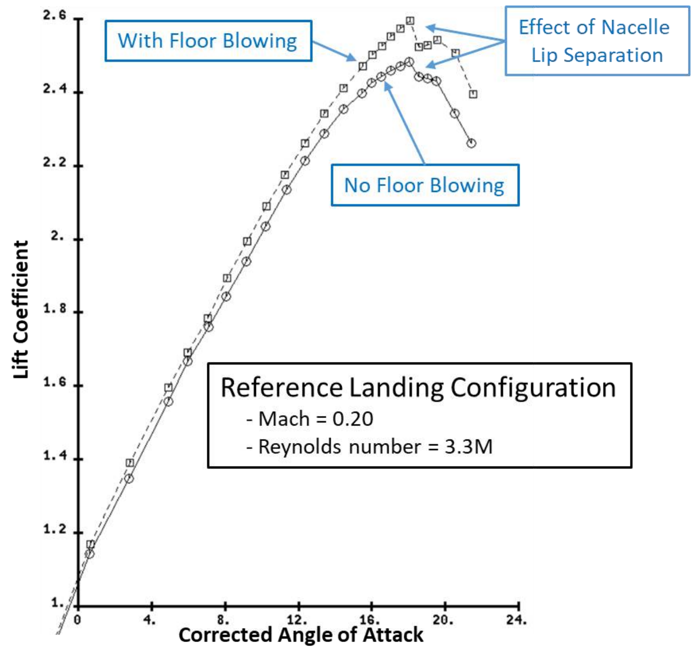

Figure 9 Reference landing configuration lift characteristics, with and without floor blowing.

Looking at how the wing is breaking down at stall, one can see that without blowing, a large separated region near the fuselage is having a significant effect on performance (Figure 10). With blowing on (Figure 11), this area of separation is much reduced, and the stall is driven by the pylon region. This latter scenario is believed to be the most representative and therefore the most desirable. It also appears that without the half model issues, the pylon region will be the dominant force driving wing stall with this configuration. It is likely that interesting flow phenomena will still exist near the body, but won't be the key driver of stall. A third feature of interest is the impact of leading edge bracket wakes on the wing upper surface. Figure 12 shows how these lead to pockets of separation at the trailing edge of the outboard wing which grow with increasing angle of attack. Add to this the impact that the nacelle chine has on the lift curve approaching stall and the net result is a very interesting and relevant set of flow physics being exhibited by this configuration, particularly its leading edge aspects.

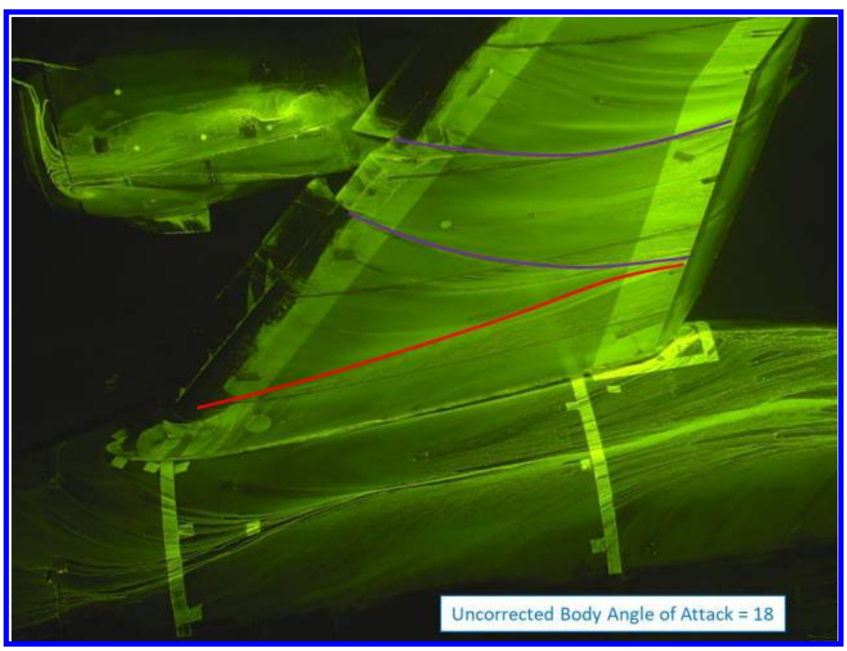

Figure 10 UV oil for reference landing configuration, without floor blowing.

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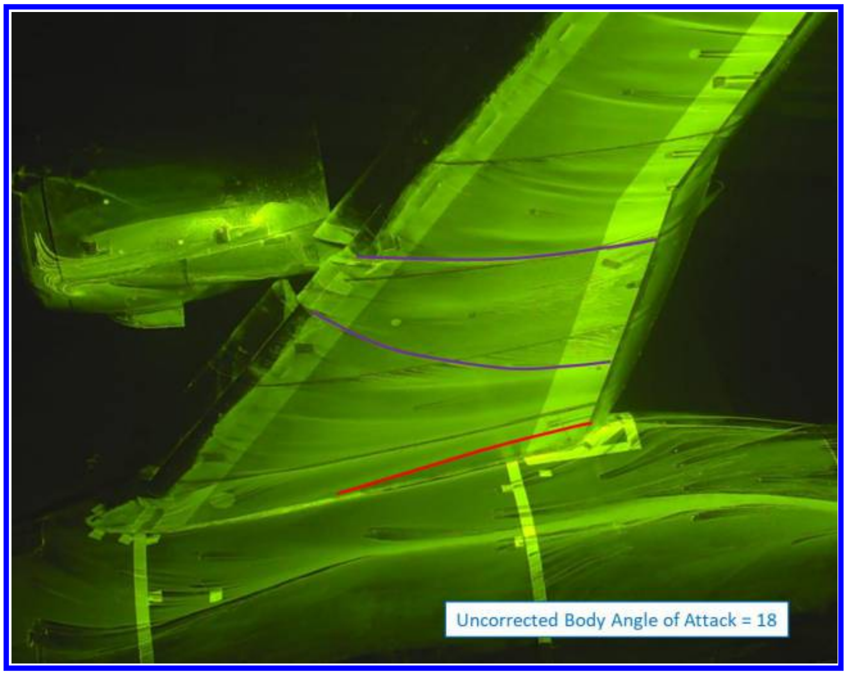

Figure 11 UV oil for reference landing configuration, with floor blowing.

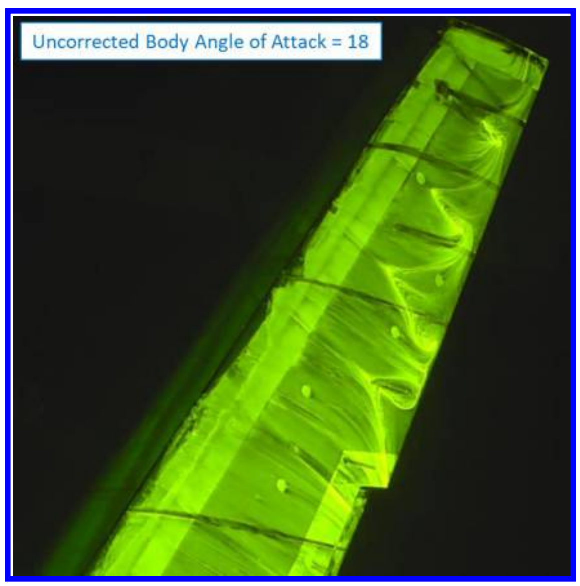

Figure 12 UV oil for reference landing configuration – outboard wing.

Looking more closely at the trailing edge, the UV oil picture for 6 degrees angle of attack in Figure 11 shows significant separation on both the inboard and outboard flaps, particularly behind flap supports. Looking at the same region at 18 degrees in Figure 12 shows that the flap separation has largely gone away. This would seem to indicate that this is a fairly aggressive configuration presenting a range of relevant flow physics through a progression of angle of attack. However, the level of aggressiveness is likely to be a function of Reynolds number. Testing this configuration at much higher Reynolds number at a cryogenic facility would likely produce much healthier flap aerodynamics, potentially capable of further improved performance through increased flap angles. Just exploiting the pressurization capability of the QinetiQ facility to increase the Reynolds number from ~3.30M to ~5.45M produced noticeably healthier flaps. However, the opposite will be true if this configuration is tested at a smaller scale facility with significantly lower Reynolds number capability. The flaps will likely be over-deflected for those conditions, produce excessive separation and therefore not be a configuration of interest.

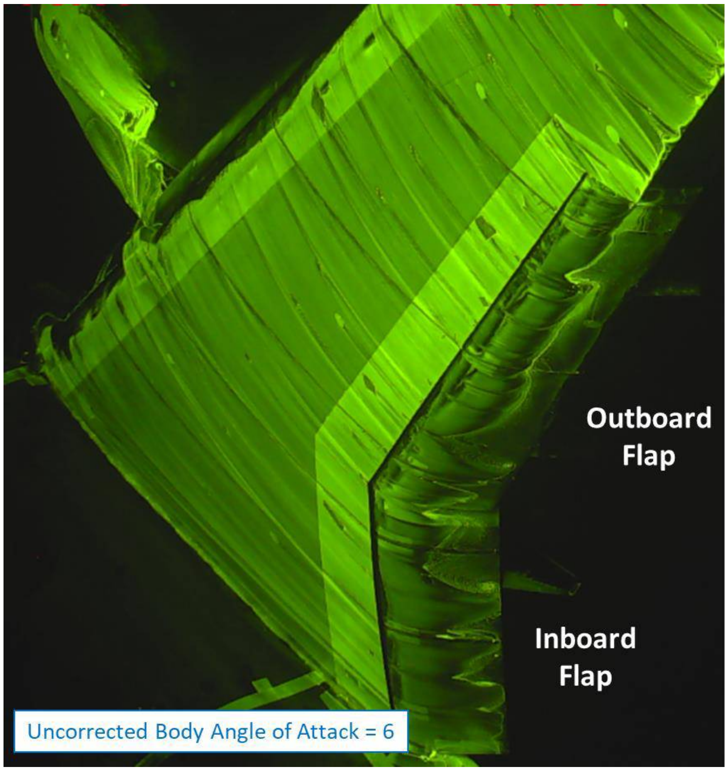

Figure 13 UV oil for reference landing configuration, 6 degrees angle of attack.

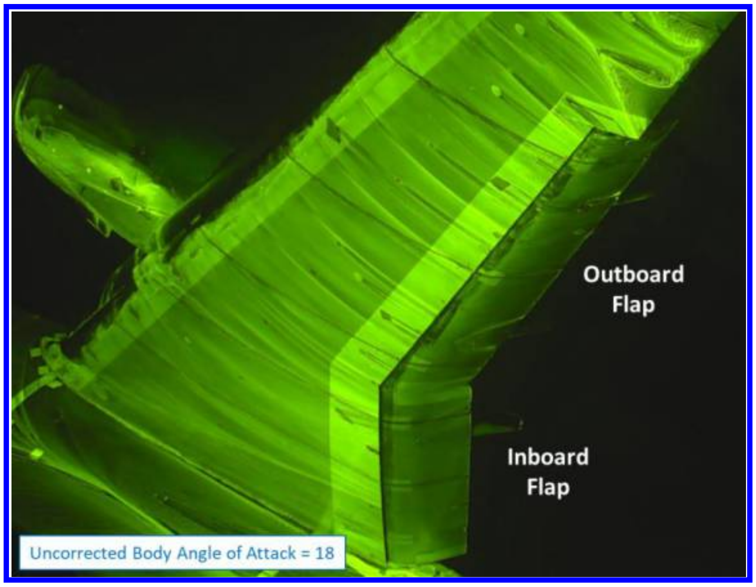

Figure 14 UV oil for reference landing configuration, 18 degrees angle of attack.

In order to produce configurations of interest at all Reynolds numbers, two alternate reference configurations have also been created that differed from each other only in flap angles. One incorporates reduced inboard and outboard flap angles by three degrees while the other increases them by the same amount. This will allow users to explore

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performance trends with flap angle and how those trends vary with Reynolds number. It will also ensure that they have at least one configuration that works well at the Reynolds number of their scenario.

B. Takeoff Reference Configuration

The takeoff configurations tested were afflicted with the same high angle of attack side-of-body issues that existed at landing. It is believed that the same conclusions drawn there (regarding having stall being driven by the pylon region) will apply to the takeoff configuration as well. There was not a lot of performance variation across the range of positions tested. Ultimately, the reference configuration chosen was the nearly same as the pretest nominal one – with one exception. The pretest geometry incorporated a small gap, primarily as it was deemed an easier configuration to prepare for CFD than one with a sealed leading edge. For the reference takeoff configuration, the inboard and outboard slats were pushed aft to seal (and then taped underneath to ensure sealing). For one, this represents a realistic configuration as many aircraft do utilize sealed leading edges for takeoff. Secondly, it essentially eliminates the impact of brackets on the wing upper surface, making the fact that our bracket architecture is not really representative a moot point. Third, it offers the opportunity to have a configuration that is more sensitive to Mach number. Lastly, it's a configuration of more interest to the acoustics community, as gapping the leading edge is generally regarded as noisy. Lift curves with and without floor blowing are presented in Figure 15.

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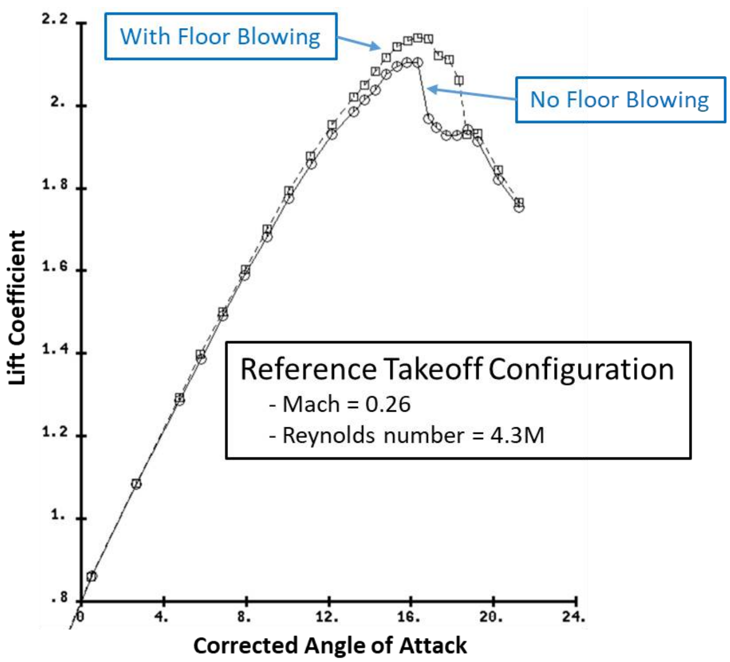

Figure 15 Reference takeoff configuration lift characteristics, with and without floor blowing.

VIII. Conclusion

A landing reference configuration of the CRM-HL and two similar alternates have been defined in support of the CRM-HL Ecosystem. These configurations have been shown to present relevant flow physics of interest to the airplane designer and CFD developer alike. A takeoff reference configuration has also been defined that presents a different yet still relevant set of flow physics. It is believed that these configurations will provide a solid base upon which to build the CRM-HL Ecosystem.

A single source of this geometry information associated with these reference configurations will be established on the NASA CRM website. Additional information will also be made available there regarding its usage, particularly in regards to designing a wind tunnel model from it. Guidance will also be provided on how to document configurations developed from the geometry.

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Acknowledgments

There has been a great deal of effort expended over the last several years to get to this point of defining reference configurations. NASA has been instrumental in initiating the geometry definition (particularly John Lin) and getting the first wind tunnel model built (led by Jared Fell). In addition, a large number of people from Boeing, NASA, QinetiQ and ATI contributed to the execution of the QinetiQ wind tunnel test, particularly other members of the test crew: Jeff Slotnick, Ashley Evans, Melissa Rivers, John Lin and Ian Smith. Lastly, members of the GMGW planning committee, notably Mark Gammon, provided substantial help in understanding the geometry and identifying and addressing issues.

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